ENABLING RESPONSIVE REAL-TIME INSPECTION OF THE AUTOMATED FIBER PLACEMENT PROCESS

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ABSTRACT

Automated Fiber Placement (AFP) is used to manufacture large and complex parts in the aerospace industry. A time-consuming portion of this fabrication process remains the inspection and quality control, which are largely performed visually after each deposited layer. This conference proceeding showcases a disruptive, responsive, and reliable solution based on the Fives In-Process Inspection system enabled by the National Research Council of Canada (NRC) Optical Coherence Tomography (OCT) sensor to perform in-process defect monitoring of the fiber layup. Measurements are taken close to the material deposition location without inhibiting the optimal machine path or slowing down the layup process. Assessment of the quality of a deposition takes place concurrently while the layup head applies material. This responsive feedback loop enables adaptive control of the AFP fabrication process. Technical details on how the OCT based inspection system's data flow has been integrated within the manufacturing process of a Fives Viper AFP machine are provided to explain the system's real-time response and high-resolution measurements. Results obtained in an industrial setting using the sensor installed on a production AFP machine are presented.

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1. INTRODUCTION

An AFP machine fabricates a part with layers of composite material ply surfaces. Each ply consists of machine courses, which are composed of a multiplicity of tows layed down in a single pass of the layup head. For example, a machine may lay up to 32 tows of 3.175 mm width corresponding to a maximum course width of 101.6 mm. A set of adjacent courses with a common orientation constitute a ply, and a set of plies constitute a part. To ensure the finished part does not contain any critical defects that may be introduced by this additive manufacturing process, each deposited ply must be inspected and reworked, if necessary, before the next ply is layed.

The implementation of a high-fidelity AFP inspection system is a sought-after solution for machine manufacturers and end-users alike. Traditional ply-by-ply manual and visual inspection methods can consume as much as 30-60% of the total AFP production time. In addition to significantly reducing production time and cost, in-process inspection provides greater repeatability, removing operator bias and enabling adaptive process control. Furthermore, it allows part manufacturers to quantitatively demonstrate how the "as-built" part truly deviates from the "as-designed" model, an information that is critical for the definition of acceptable manufacturing tolerances.

The implementation of a real-time AFP inspection solution that does not impede the process, but rather becomes an integral part of the equipment, represents quite a challenge and has only achieved partial success in past implementations. An inspection system using a laser analog distance sensor was patented as early as 1996 by Kitson et al. The system could be mounted on the head of an AFP machine to perform real-time detection of predictable geometry-induced end of band gaps and overlaps as well as unpredictable manufacturing-induced gaps and overlaps along the length of a course [1]. Since then, a number of systems based on laser line triangulation sensors have been investigated to great depth as an inspection technique capable of defect detection [2-4]. Finally, thermographic sensing techniques have been used to demonstrate the feasibility of detecting defects by their unique temperature signature [5, 6]. While these systems have demonstrated some success in a few applications, a number of material and integration challenges limit their widespread application.

In previous papers, an automated fiber placement inspection system based on Optical Coherence Tomography (OCT) was presented [7, 8]. This sensing technique is employed to address the key challenges that must be overcome for an AFP inspection solution to be effective. This modular solution allows for a compact optical scanner design which is well integrated on the AFP head. The measurement rate of OCT also enables inspection without slowing down the fabrication process. The robust sensitivity of OCT is crucial to perform accurate measurements on any composite material, which often returns low optical power.

This paper presents some background on the OCT technology along with its key benefits applicable to in-process, real-time AFP inspection. The process of developing a 3D "as-built" dataset concurrent to part fabrication is described. The part manufacturing workflow, coordinate system management, and inspection data processing pipeline explain the integration of the inspection system within the AFP machine. Finally, measurement results from the inspection system integrated with a Fives Viper AFP machine are shown.

2. OPTICAL COHERENCE TOMOGRAPHY IMAGING

Optical Coherence Tomography (OCT) is an imaging technique initially proposed in 1991 that is similar to ultrasound imaging; however, with OCT, optical waves are used to probe the sample instead of mechanical waves [9, 10]. OCT is primarily used in the biomedical field to image transparent and semi-transparent tissue such as the retina and artery walls since it can penetrate up to a depth of a few mm under the tissue's surface [10]. Today, many commercial OCT systems are available, and the technique is used clinically in medical applications to diagnose patients. Outside of the medical world, OCT has also found a niche application in real-time welding inspection [11].

A simplified representation of the OCT measurement system employed in this work is depicted in Figure 1. It is based on the swept-source OCT technology [10]. A laser emits light, continuously sweeping over a broad wavelength spectrum, in an interferometer that divides the light between a reference arm and a sample arm. The reference arm has a mirror at the end of its optical path while the sample arm directs the light towards the object to be inspected. The light returned by the reference mirror and the sample is recombined and sent to a detector. The interference between the light returned from each arm contains information, encoded in the different wavelengths, on the mismatch in optical length between the path going through the reference arm and the path going through the sample arm. The location of any reflecting structures in the sample arm is recovered from a Fourier transform of the interference signal. An important feature of this technology is that the scanning system in the sample arm can be tailored to any size and shape required to accommodate a wide variety of applications and available space.

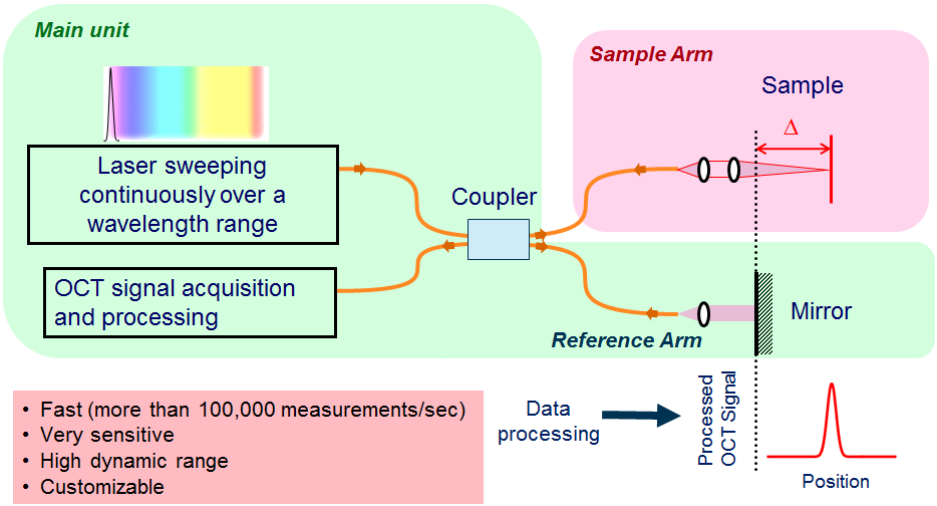


Figure 1: A simplified representation of an Optical Coherence Tomography system.

The carbon fiber based prepreg materials widely used for AFP are opaque to light, thus preventing penetrative measurements within the material. Nonetheless, the technique is a highly effective implementation of surface profilometry. It is capable of accurately imaging carbon fibers because of its high resolution and robust imaging capabilities. Previous publications have discussed in detail, the beneficial characteristics of OCT based measurement systems [7, 8]. They will be summarized again below as background.

The benefits of using OCT in a real-time sensing application are fivefold. Firstly, the scanning-head, or sample arm depicted in Figure 1, can be separated from the rest of the inspection system, facilitating low footprint sensor integration within the AFP head, which has limited space and inertial mass available for additional hardware. Secondly, the optical path is confocal (light is sent and received from the same pinhole point), thus, facilitating miniaturization and optimal mounting configuration of the scanning-head. Furthermore, because of the confocal optical configuration, light that does not originate from the focal point on the sample surface is rejected by the light collection optics of the sensor scanning head, giving OCT based measurement systems greater immunity to ambient light noise [11]. Thirdly, the measured signal varies proportionally to the square root of the intensity of the signal collected from the illumination of the sample surface. This dramatically increases the dynamic range of light intensity that can be handled by the system. In other words, OCT based measurement systems can perform measurement on surfaces returning high or low quantity of light without the need to change the sensor configuration to accommodate these variations in the signal. Fourthly, the system can detect weak signals from a sample surface because the signal returned from the reference arm remains high which helps maintain a measurable interference pattern. Since carbon fiber based prepreg materials return less light when inspected at higher incidence angle, this feature contributes to maintain accurate surface measurements with OCT systems even at high incidence angles [8]. Finally, the measurement range of OCT systems can be adjusted dynamically to keep track of surfaces with complex geometries. Modification of the length of the reference arm with a delay line and displacement of the focal point enables on-the-fly adjustments to maintain the inspected surface within the sensor's measurement range even if it moves closer to or away from the sensor head.

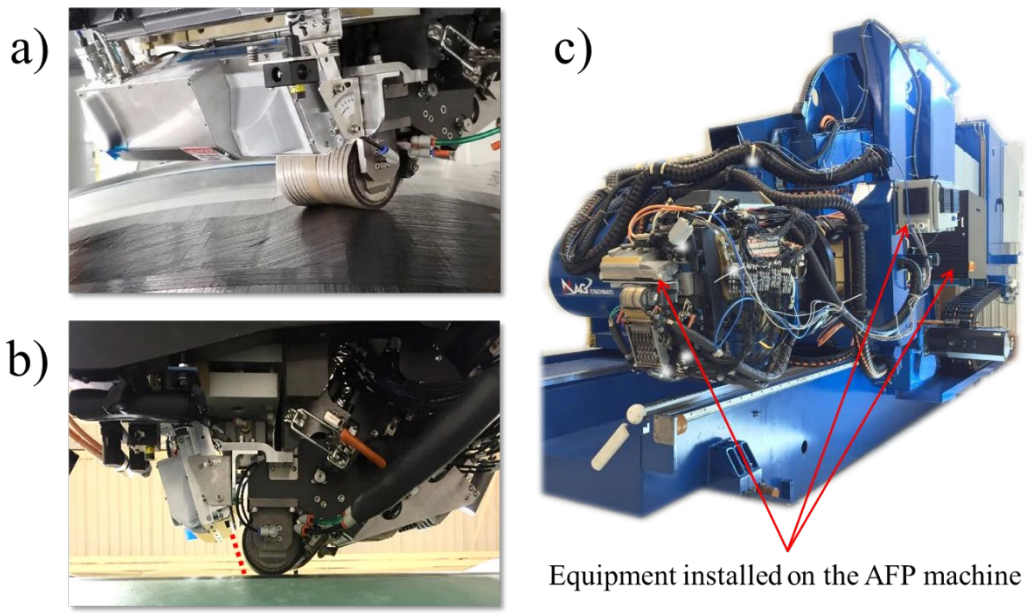


Figure 2: (a-b) OCT scanning head installed on an AFP head at an inclined angle. (c) All measurement system components installed on the Viper 4000 AFP machine: scanning head and the two enclosures (gray and black).

Figure 2 shows the OCT hardware integrated within NRC's Fives Viper 4000 AFP machine located at Stelia Aerospace in Mirabel, Quebec. Figure 2 a) and b) show the sensor scanning head

installed on the AFP head. As the course is layed, the sensor scans a line perpendicular to the layup direction in the part's surface plane, after the compaction roller. The scanning head is inclined with respect to the compaction direction to obtain measurements as close as possible to the compaction roller nip point. This angle is roughly 20° and can be seen in Figure 2 b) where the optical path is depicted by the red dotted line. As shown in Figure 2 c), all the remaining hardware components are installed in two enclosures mounted on the side of the machine where they do not impact the high accuracy and acceleration of the layup head. The interferometer's sample arm, referenced earlier, extends from the black main enclosure in Figure 2 c) to the scanning head.

3. PART DEVELOPMENT AND MANUFACTURING WORKFLOW

In order to determine whether located features are classified as defects, the "as-built" sensor measurement scans must be compared to the "as-designed" digital part model. To do this, multiple data sources must be processed and combined correctly.

The process begins with the part design data. This data starts as a 3D solid model and is converted into composite ply surfaces via a CAM tool like Siemens FiberSim or CATIA Composite Workbench. These surfaces along with the fiber orientation of each ply (a.k.a. the part ply book) are the basic building blocks needed to generate an AFP machine program and represent a digital version of the perfect part. Next, the machine programming software tool is used to convert the ply surface definitions into an AFP machine program. The Fives Advanced Composites Environment Suite (ACES) offline programming software was used for this work. ACES imports the ply data from a CAM tool and generates a machine program, ply boundary definitions, and the inspection assets required to transform the measurements from the inspection sensor reference to an absolute, located, 3D point cloud dataset, namely, the "as-built" part. It accounts for the relationship of the tool surface to the layup head during the generation of this machine program to avoid collisions while maintaining contact. After the part program is generated, it is loaded into the AFP machine control system and used to manufacture the part. Machine alignment is performed prior to the layup to determine the relationship of the program to the tool surface. During layup, the In-Process Inspection system processes data simultaneously from both the AFP machine (head locations) and the inspection sensor (surface profiles measurements) to create a surface map of the ply. A profile is a collection of relative elevations or heights along a scanned width of the part surface. This custom Simultaneous Location and Mapping (SLAM) software module is a key ingredient to a responsive measurement system. The last step in generating the "as-built" part is the real-time alignment and comparison of the 3D point cloud of sensor measurements to the original CAD ply surfaces. The differences between these two datasets are candidates for deviations and defects. Those falling outside of manufacturing tolerances must be reworked before continuing layup of the next ply. With the outline of the process summarized above, the hardware alignment and required dataset reference frame transformations must be well defined.

4. COORDINATE REFERENCE FRAME MANAGEMENT

In order to correctly align the datasets in the process described above, the coordinate reference frames of each source must be carefully defined and managed. The following list describes these reference frames and Figure 3 demonstrates their relation to one another in the part workflow.

1. Design Reference Frame (DRF) – The part coordinate system which shows its location within the parent assembly. This definition originates from the customer's design or a larger assembly within which the part is integrated (e.g.: airplane coordinate system).

2. Program Reference Frame (PRF) – Once the specific AFP machine model and layup tool is defined, the program reference frame represents the initially aligned coordinate reference used in the machine program during New Production Introduction (NPI). This program is "posted" from the offline programming tool to the AFP control system.

3. Machine Reference Frame (MRF) – When the program is setup on the machine, the specific location of the layup tool in relation to the AFP head is determined via a probing process. The offset parameters from the ideal program is calculated and stored in the AFP control system. This frame is also sometimes referred to as world-coordinate frame since it describes the coordinates commonly used by the machine operators.

4. Sensor Reference Frame (SRF) – The inspection system provides a 2D profile for each scan line. Currently, this reference frame originates in the optical scanner of the OCT system. The origin of this reference frame moves with the AFP head relatively to the tool during the fabrication process which makes it a complex operation to accurately convert coordinates from the SRF to the DRF.

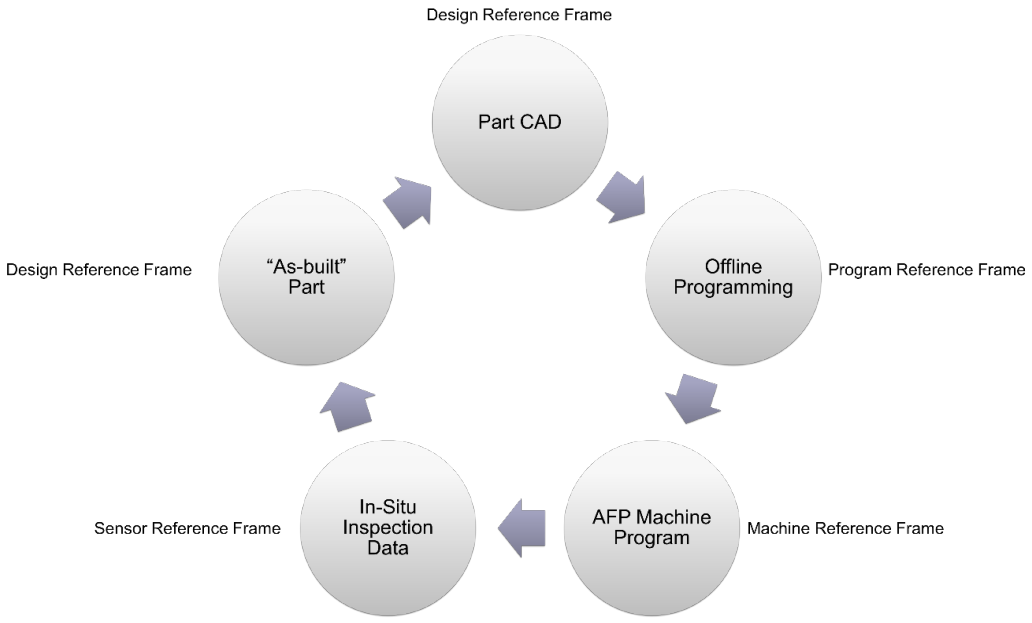


Figure 3: Relationship between reference frames used in a part workflow.

5. INSPECTION DATA PROCESSING PIPELINE

The data processing required to generate the "as-built" component involves two major activities to go from offline programming to processed data. First is the New Product Introduction (NPI) activity where the offline programming application provides the part program to the AFP machine and the part plan to the In-Process Inspection system. This step is a one-time process and is completed before layup. The second activity is the layup of the part and simultaneous streaming

of inspection sensor data through the real-time processing pipeline. This step, outlined in Figure 4 a), involves first processing high bandwidth raw datagrams generated by the scanning head transducer into surface profiles during the scan conversion step. Next, these surface profiles scans are synchronized with the machine position stream before being fused together using the Simultaneous Location and Mapping (SLAM) module of the inspection system. The refined data obtained at this stage can then be stored and used to identify features, determine if they are defects (out of tolerance features) providing immediate process control information to the AFP operator.

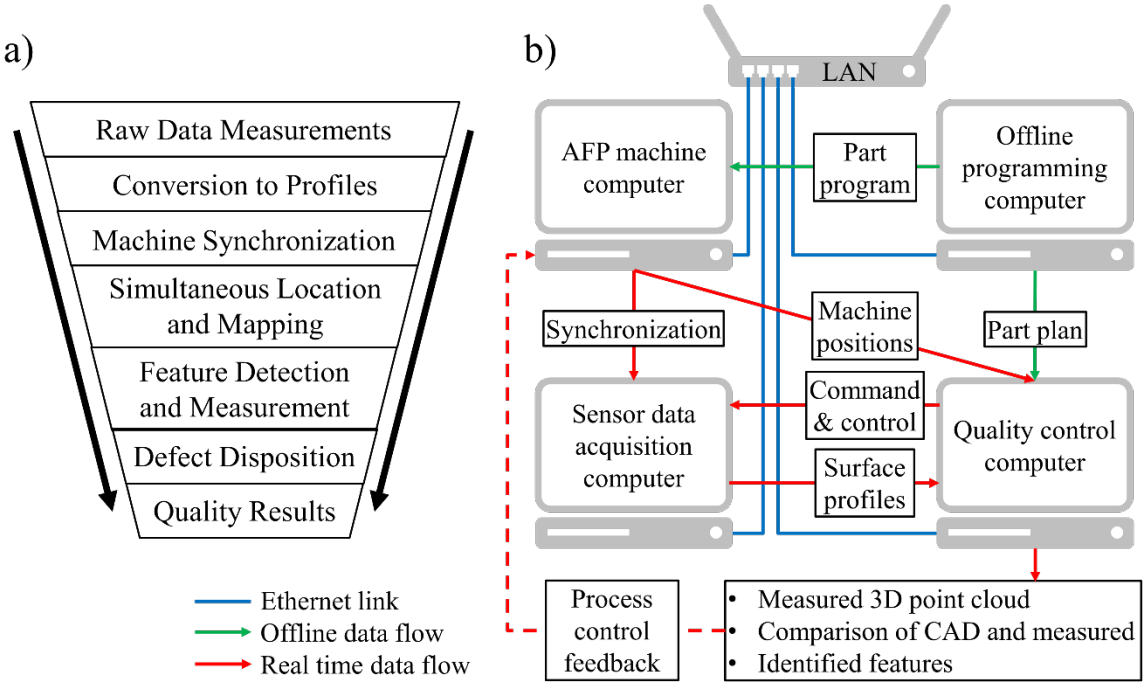


Figure 4: Overview of the data pipeline of the inspection system integrated to an AFP machine. (a) Contextual view of the real-time streaming pipeline leading to quality results. (b) Links between elements of the system.

Figure 4 b) shows the basic data flow between the offline programming computer running ACES, the AFP machine, and the In-Process Inspection system. This diagram shows how data is collected and processed into a real-time "as-built" part dataset. Prior to layup, the offline ACES programming software is used to generate the part program which is sent to the AFP machine computer as well as the part plan which is sent to the defect analysis computer (green arrows). This step is the one-time process completed before layup. Once layup starts, there is an active synchronization process between the In-Process Inspection system measurements and the AFP head's position and orientation across the tool surface. Both of these data streams are sent to the quality control computer where the surface profile data is processed into a located 3D point cloud ("as-built"), compared to the layup plan ("as-designed"), and analyzed for out of tolerance defects. These actions, shown as red lines in Figure 4 b), are performed concurrent to the AFP layup with results available immediately after a completed course to facilitate prompt feedback and determine if the process is in control and can continue layup.

IN-PROCESS INSPECTION RESULTS

To demonstrate the capabilities of the technology, measurements were collected in a production-like environment with the OCT based In-Process Inspection system mounted on the Viper 4000 AFP machine. The OCT based inspection system has the ability to detect a variety of defects. These defects are grouped into three types: Gaps/overlaps, placement errors (missing tow, tow end), and topical defects (splice, wrinkles, twists). Figure 5 shows a single course containing many tow starts and cuts layed up on a flat tool. A perpendicular full course, also layed up by AFP formed the underlying layer. This trial demonstrates the ability of the system to accurately detect both gaps and overlaps between adjacent tows as well as tow end placement.

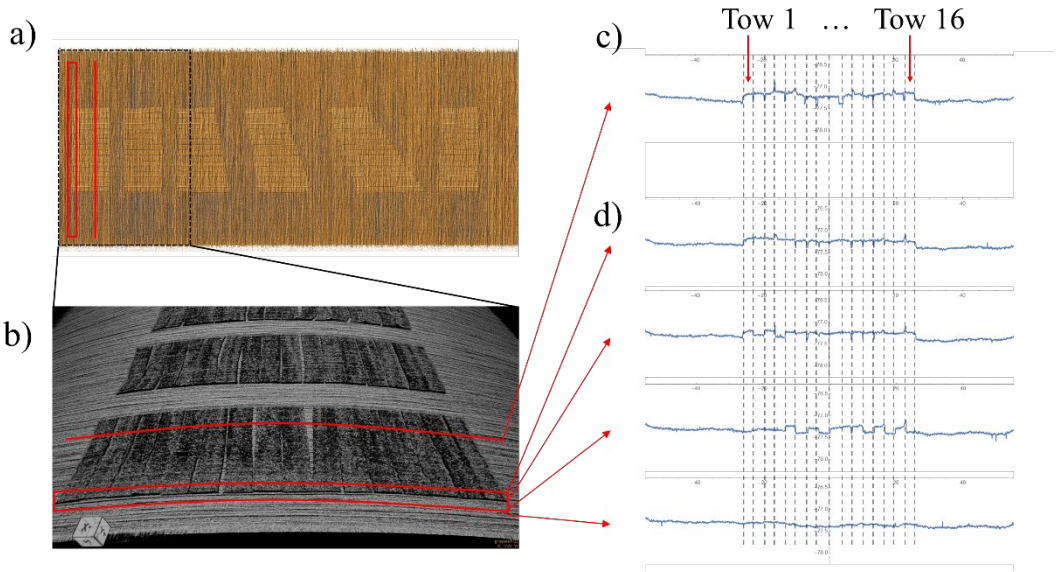


Figure 5: Trial measurement. (a) Image formed of consecutive profiles in the sensor reference frame. The image dimension is approximately 1500 mm in length by 100 mm in width. (b) Raw tomography volume data from which profiles are extracted by performing a peak detection. (c) Visible gaps and overlaps in a profile. (d) Four consecutive profiles that cover a start of band. The profile width covers 100 mm and the depth scale covers 2mm.

The intermediate measurement results from this trial are shown in Figure 5 a), where consecutive profiles from the sensor are combined to form a heat map image. Each pixel represents a single depth measurement and the heat map scale covers approximately 2 mm of depth in Figure 5 a). Figure 5 b) is a 3D image, with transparency, of the raw data showing the whole tomographic volume measured by the sensor. The points located at the surface provide the strongest signal and are the most apparent in the rendering. These points are isolated and located with a peak detection algorithm to provide depth measurements. The collection of depth measurements along the scan line are then regrouped to form surface profiles like those shown in Figure 5 c) and d). The profile shown in Figure 5 c) was taken in the middle of the deposited course. Based on the known nominal tow width and number of tows in a course, regions of interests can be identified in the profile. In this case 16 tows were layed up and identified. At the junction of adjacent tows, the presence and width of gaps or overlaps are measured. Figure 5 d) shows four consecutive profiles taken at the beginning of the course. Each individual tow's start location can be identified as it appears.

Figure 6 shows an example of splice, wrinkle, twist, and missing tow defects that were manually added to an existing course, with an 8-ply quasi-isotropic underlying laminate. Each pixel in the heat map images shown in Figure 6 b) to f) represents a single depth measurement. As seen in Figure 6 b) to f), all defects can be readily identified and classified despite the build-up of underlying layers containing numerous uncorrected gaps and overlaps, resulting in the topology visible in the figure. This topology is enhanced by the heat map scale that covers approximately 1 mm of depth.

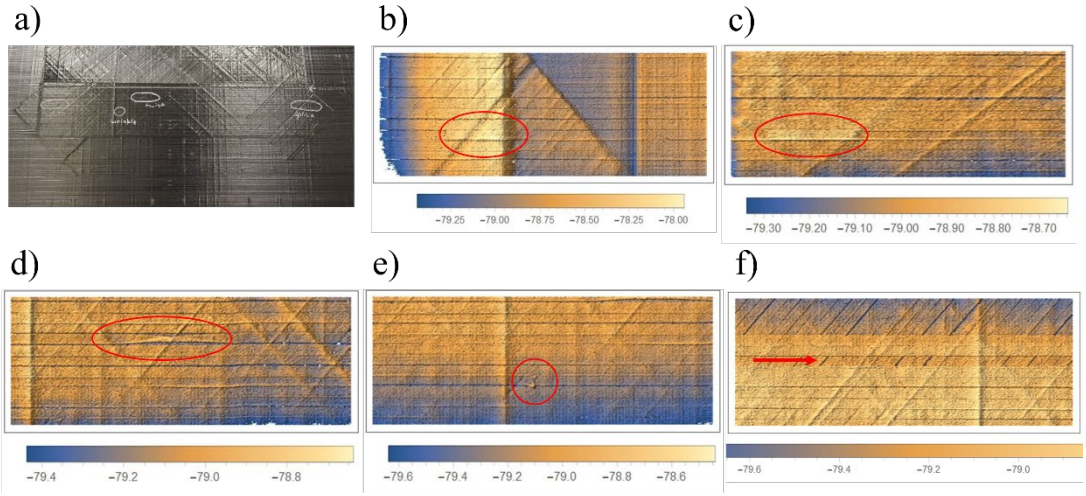


Figure 6: Flat surface with various defects. (a) Picture of the surface. (b-c) Tow splices. (d) Tow twist. (e) Tow wrinkle. (f) Missing tow. (b-f) The images dimensions are approximately 100 mm in length by 40 mm in width.

The intermediate results described above only show one basic level of feature detection offered by this technology. The data is presented in a relative reference (Sensor Reference Frame), and thus, has limited application on more complex part geometry. In order to demonstrate the ability to accurately locate and correct points in space, a single course layed up over the bevel section of complex shaped tool was measured. The course is highlighted in green in the ACES offline programming application in Figure 7 a). When the layup surface contains complex curvatures, the AFP head reorientation and change of speed during layup cause apparent image distortions from the true ply surface, as shown in Figure 7 b). These are evidenced by the discoloration (large blue triangular shadow followed by large bright yellow section) and apparent irregularities in the orientation of the tows in the underlying ply. Note that these discoloration represent a large topographic feature since the heat map scale covers 20 mm of depth in Figure 7 b). To correct for this artifact, the profiles measured by the sensor are transformed from the relative Sensor Reference Frame to an absolute 3D point cloud in the Design Reference Frame.

The procedure for creating a 3D point cloud described in this paper is applied and the results are shown in Figure 7 c). After converting the measured data to a 3D point cloud, the artifacts from machine reorientation and change of speed during layup are gone and the surface no longer appears distorted. At this stage, the “as-built” part can be directly compared to the “as-designed” CAD model.

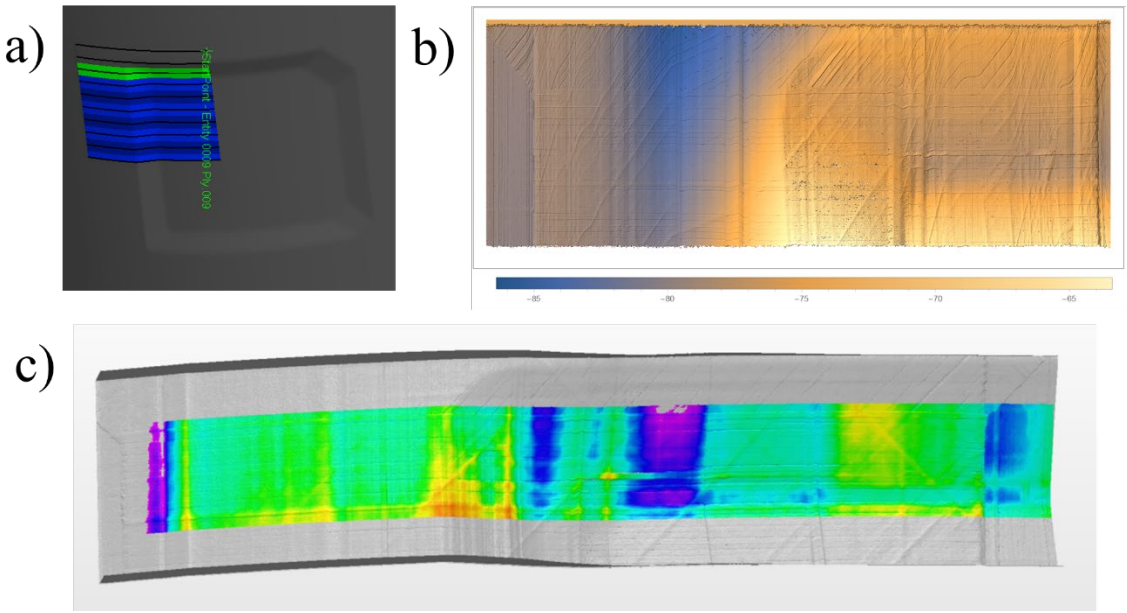


Figure 7: Measurement on a curved surface. (a) View of the programmed course in ACES (in green). (b) Consecutive profiles in the Sensor Reference Frame. The scan is approximately 100 mm wide, but dimensions along length are distorted. (c) 3D point cloud of the "as-built" part, located on the tool CAD model.

6. CONCLUSION

Gathering comprehensive surface information of a composite part with an in-process inspection system during its real-time AFP fabrication is a key enabler for comparing an "as-built" part to its "as-designed" specification. This paper describes how the NRC OCT sensor paired with the Fives In-Process Inspection system has overcome these challenges to generate accurate 3D point cloud datasets which can be used for inspection, process development, and real-time process control. The seamless integration of this measurement platform on a production AFP machine was outlined and results were shown to demonstrate the implementation of the solution.

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